

A SMARTER LOCK: APPLYING RECENT AND EMERGING TECHNOLOGY TO IMPROVE LOCKOUT/TAGOUT

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ABSTRACT

The lockout/tagout (LOTO) of mechanically and electrically powered equipment at mine sites is often a multistep process and is often the root cause of machine-related injuries in the mining industry. Such accidents are commonly the result of inadequate LOTO protocols, resulting in inadvertent machine startup during maintenance. LOTO is frequently complex and time-consuming, two factors that sometimes contribute to human error and subsequent hazardous situations. The National Institute for Occupational Safety and Health (NIOSH) is conducting research aimed at the implementation of emerging technologies to improve worker safety. Part of that effort is exploring the application of new technologies to improve LOTO protocols. As part of their research, NIOSH is researching a new type of lock design to augment existing LOTO processes and improve the “situational awareness” (SA) of workers during maintenance activities. The lock design comprises an evolutionary approach to existing wireless locks with regards to range, security, and ease of use. This paper will detail current NIOSH-developed prototypes, highlighting the advantages and disadvantages compared to traditional and currently available wireless locks. Also included are a description of an “iLOTO system” and how such a solution can be integrated with a broader safety monitoring system.

Keywords: IoT, lockout/tagout, machine safety

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INTRODUCTION

Improper lockout/tagout (LOTO) has contributed to many fatal and nonfatal accidents in the mining industry. Ruff and others have shown that one-third of fatal, machine-related accidents at surface mines involved improper LOTO procedures as a contributing factor [1]. Another recent study shows that 25% of all the fatalities during maintenance and repair can be attributed to improper LOTO [2]. In response to the prevalence of such accidents, the U.S. Mine Safety and Health Administration (MSHA) issued a request for information (RFI) that included the following: “Since 2007, there have been 17 fatalities related to working near or around belt conveyors, of which 76 percent were related to miners becoming entangled in belt drives, belt rollers, and discharge points. Factors that contribute to entanglement hazards include inadequate or missing guards, inadequate or an insufficient number of crossovers in strategic locations, and/or inappropriate lockout/tagout procedures. Systems that can sense a miner’s presence in hazardous locations; ensure that machine guards are properly secured in place; and/or ensure machines are properly locked out and tagged out during maintenance would reduce fatalities” [3].

A thorough examination of MSHA fatality reports in the metal/nonmetal (MNM) mining sector from 2005 to 2019 showed that there were 32 fatalities where LOTO procedures were either not followed, circumvented, or not in place. Analysis of the MSHA root cause codes for those fatalities indicated that the most frequent cause (34%) of fatal injuries was management’s LOTO protocols being inadequate for the job, followed by injuries where there was a failure to attempt LOTO protocols (16%) as shown in Figure 1.

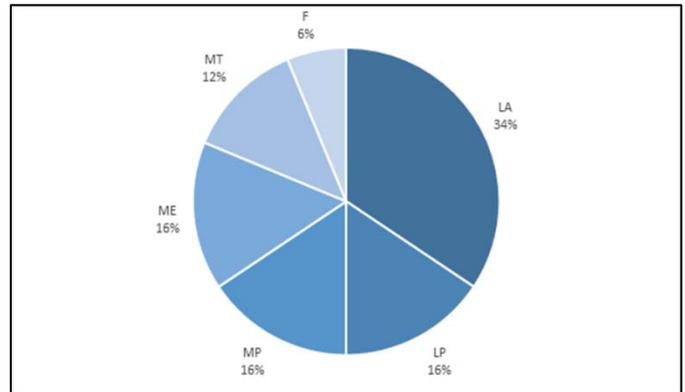


Figure 1. Root cause codes of fatally injured victims. LA = management’s LOTO protocols were inadequate, LP = failure to attempt LOTO protocols, MP = management failure to establish appropriate LOTO protocols, ME = management not ensuring that workers comply with LOTO protocols, MT = management failure to properly train the workers to perform the task, F = failure to fully complete the LOTO protocol.

It is not clear why LOTO protocols are often inadequate or not attempted as shown in Figure 1. A reading of the accident narratives indicates that there is sometimes simply a lack of awareness as to how to properly lockout the equipment. Also, since LOTO can sometimes be time-consuming, especially when multiple people need to be involved to lock out and tag out a piece of equipment, additional reasons for circumvention might include trying to get a job done more quickly (in the natural tendency for humans to get short-term gratification by completing a job quickly). It is also easy for humans to negate vague or unlikely consequences or to rationalize when they are under pressure. Examples of possible reasons might include, “I just don’t have time” or “someone else did it this way and there were no consequences” or “this lockout is not really necessary and I’m sure someone just required it to cover their legal obligations.”

To address the prevalence of LOTO-related injuries, researchers at the NIOSH Spokane Mining Research Division (SMRD) are exploring the potential application of new technologies to provide cost-effective intelligent machine monitoring and LOTO systems for improved worker safety [4]. The envisioned intelligent LOTO (iLOTO)

system includes the use of a wirelessly connected padlock combined with a web browser-based application to provide a user interface for the iLOTO process. The web app will ideally allow for a wide variety of sensors/devices to be used with the system and does not necessarily require a connection to the internet since it can be locally hosted by an onsite server connected to a local network.

Researchers envision a system that will mimic traditional LOTO processes as closely as possible, while taking advantage of new opportunities that iLOTO can introduce to the process. Both approaches utilize a padlock, but in the case of iLOTO the padlock will be replaced by a wirelessly connected digital lock and associated mobile software as a way to make the LOTO process easier to execute and thus less likely to be circumvented. The wirelessly connected lock and iLOTO system being developed by NIOSH researchers will be used to demonstrate and evaluate the use of iLOTO for a specific application in collaboration with our partner, Central Pre-Mix Concrete a CRH Company.

In this context, iLOTO is a means of maintaining all existing LOTO requirements while providing additional information to interested personnel. The iLOTO system will be driven by a user interface that includes an electronic form which lists everyone involved in the LOTO procedure; this list can be compared to real-time data from the digital lock to ensure each person involved has also “virtually placed their lock” by way of electronic credentials either via the user interface or on the lock itself. This becomes advantageous when multiple people are involved in a LOTO protocol. Presently, when multiple users are involved in a LOTO process, a lock box or hasp is used. The digital lock is able to achieve the same multiple-user LOTO as a lock box or hasp and has the key advantage that all locking and unlocking actions are recorded and archived with timestamps, and this information can be viewed remotely at any time. Further, this information can be compared to the breaching of access points and the deenergizing of equipment.

The user interface will generate information which will indicate the LOTO task currently being performed. This will be done by transferring the current LOTO paperwork to an electronic system, i.e. an electronic LOTO form. Since documentation of LOTO is already required, an electronic form does not represent an additional burden. Moreover, the completion of the LOTO form can readily be synchronized with sensors located on access points and electrical safety disconnects (and the lock itself) to ensure that the LOTO procedure is followed. An example of a similar system is described in previous NIOSH publications [4, 5]. Another advantage of iLOTO is that it has potential to improve worker communication during maintenance activities, as there have been incidents where MSHA-reported accidents occurred due to miscommunication. An example of a remedy would be when one worker locks out an electrical or mechanical system and other workers can verify on their personal device that the system is properly locked out.

To achieve this goal of an iLOTO system, NIOSH researchers are developing a digital (processor controlled) “intelligent lock” (iLock) prototype that will be used to demonstrate iLOTO at an active mine. The concept of a wirelessly connected and controlled lock is not new; however, for the iLOTO application none of the existing locks satisfy the requirements. With the advent and proliferation of wireless technologies, several commercial vendors are developing wireless locks and locking systems. Examples include the Schlage door locks, Masterlock’s Bluetooth locks and Nokey’s variety of keyless locks. One hallmark of these new technologies is that they are based on internet-accessible web apps that control the lock’s function and user interaction with the locks by phone or computer and frequently come with a monthly fee. The data communication pathways are typically based on common wireless protocols such as Bluetooth and Wi-Fi, and the data is sent through a secure Application Programming Interface (API) that is uniquely tied to their product and uses a predefined user interface.

The proprietary/secure APIs used for currently available wirelessly connected locks prevents their use in a diverse array of LOTO scenarios and precludes their integration within custom iLOTO

user interfaces. To enable integration of the iLock with the existing NIOSH wireless network, the data from the lock must be available in an easily interpretable format to be tied into the mine’s existing human machine interface (HMI) or a custom user interface. This requirement is what would be considered by those involved in platform development as open at the “demand-side platform user” [6], and a smart lock of this sort is not commercially available. This lack of commercial availability was the key driver for NIOSH to develop the prototype iLock, which by design will be a demand-side open platform lock. Since this type of lock is, by definition, not secure, its use will be limited to initial prototype demonstrations primarily for the evaluation of what impact the iLock will have on the safety of workers. Prior to adoption of the lock for daily LOTO procedures, proper security measures must first be taken.

To achieve improvements in worker safety, the iLock system must:

- 1) Be remotely accessible by approved personnel who may thereby add or remove their virtual lock
- 2) Only be unlockable by the individual who physically places the lock after all virtual locks have been removed
- 3) Enable a list of all applied virtual locks, visible remotely and on the lock display
- 4) Provide an indication of the lock (or LOTO) status on the lock itself
- 5) Withstand typical environmental conditions consistent with mining
- 6) Allow for locking and unlocking without wireless connectivity; this extends to the physical locking by the individual placing the lock and all others involved.

Developing the iLock prototypes

The first prototype iLock was built in collaboration with the Center for Engineering, Design and Entrepreneurship at Gonzaga University. The student prototype consisted of three modules (Figure 2). The locking module features a dual-cylinder locking mechanism, the servo actuator, securing plate, and the shackle. The electrical “stack” module controls communication to the lock, operation of the servo, and displays the locked out or unlocked state of the lock. The servo is connected to the main board and coded to rotate 90 degrees to correctly operate the locking mechanism. Both modules are mounted in a two-part enclosure that provides impact protection of the lock, as well as environmental protection of the internal components. The upper part features a cutout for an e-ink display and access to the USB type C charging port, while the lower part features cutouts for the shackle movement.



Figure 2. From left to right: Locking Mechanism Module, Electrical “Stack” Module, Full Assembly with Outer Casing.

The prototype was 3D printed in white nylon and has an overall footprint of 4” x 3” x 2.5” with a shackle length of 5.3”. The prototype was built using commercially available off-the-shelf parts, in order to expedite the prototyping timeline, at the cost of size and weight. Selections included using a Raspberry Pi 4 as the main logic board, due to its compatibility with off-the-shelf components, and an 1820 mAh LiPo battery and break-out board consisting of a full uninterrupted/uninterruptible power regulator. This additional board was mounted on top of the Pi, communicating and delivering power using 16 GPIO pins. The board has the functionality to read and report

battery status, as well as to initiate a deep-sleep state on the Raspberry Pi while retaining Bluetooth connection to the gateway, awaiting an interrupt signal to turn the Pi back on again upon a lock/unlock request. An e-ink display receives commands from the web-application and displays information, including a list of who has virtually locked the lock.

For prototype 1 the typical connectivity scheme found in commercially available connected locks (i.e. lock to phone/tablet and then to the web) was eliminated. Instead, the method of communication between users and the lock followed the diagram in Figure 3. A phone or computer is used to connect to the cloud application, and once in the application, the user can access any of the functionalities, such as setting up a lock or tagging one. Once the user chooses a function, the application will send a signal through the gateway and to the lock to perform the function. For the lock to communicate feedback to the user, the same path is traversed backwards.

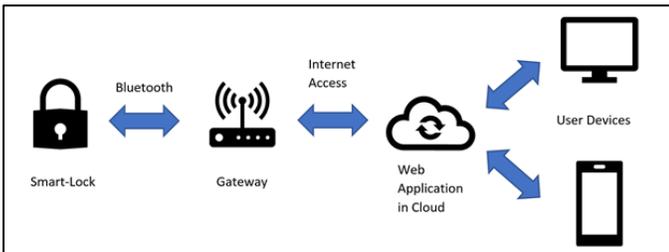


Figure 3. Connectivity scheme used for prototype-1 iLock.

While prototype-1 was functional and met the original design goals, after in-house testing it was decided that another prototype would be developed. The second prototype was designed with two primary improvements in mind: 1) reduce the lock footprint and 2) improve the wireless range.

To reduce the footprint of the lock while not compromising the lock's strength, a small (6-mm diameter) DC gearmotor (motor and gearbox) was chosen, increasing the torque available to actuate the locking mechanism (Figure 4). Both the mechanism and motor supports were designed to minimize strain on the motor to further reduce torque requirements, thus any force applied in unlocking the lock is imparted to the stable framework of the lock body rather than the motor.

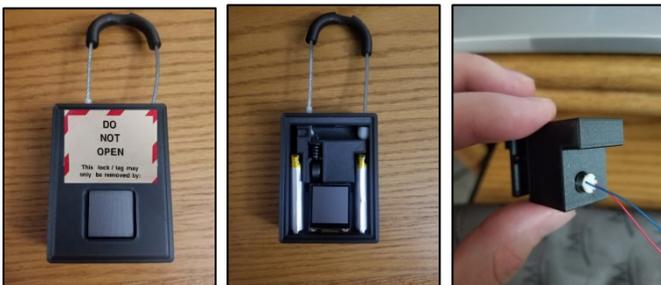


Figure 4. Prototype-2 iLock with reduced footprint.

Further reduction of the footprint was achieved by eliminating the shackle, which helps reduce the footprint since both sides of the shackle need room to move inside a traditional lock. The shackle was replaced by a cable that has one end anchored in the outside casing, while the other end comprises a swaged knob that slides into the locking mechanism. Further reduction in size was achieved by making the depth of the case as shallow as possible, carefully sizing the batteries and the electronic stack accordingly, and by designing the cover plate to fit flush with the e-ink screen, and containing a window through which the screen can be read.

To further reduce the footprint and to achieve improved wireless range, the lock was designed with embedded LoRaWAN (Long Range Wide Area Network) communication hardware, utilized for communication between the iLock and the gateway. LoRaWAN is a

type of LPWAN (low power wide area network) and is a good fit for this application. LPWANs enable long-range communication with low power consumption from the end device. This makes LPWAN a good choice for a smart lockout/tagout solution that might be distributed around the entire mine. Other LPWAN technologies, notably cellular based LTE-CAT-M and NB-IOT, were considered and have the advantage of not requiring installation of gateways on the mine's network. However, cellular service may not be present at some mine sites or penetrate some mine structures underground.

As with prototype-1, a PC board "stack" was constructed, and the dimensions were minimized in order to keep the overall surface area of the lock as small as possible. A set of four printed circuit boards (PCBs) comprised the "stack." A small, low-power LCD is affixed to the first PCB. The dimensions of the LCD defined the surface area required by the electronics "stack" on the bezel. Also included on the first PCB is a Lithium-ion battery charger and power supply. The second PCB in the stack contains a Microchip WLR089U0 LoRaWAN module, while the third PCB contains control circuitry for the lock's actuator. A final fourth PCB contains the LoRaWAN antenna.

The lock communicates via LoRaWAN gateways to the central LoRaWAN server. New locks are commissioned and added to the network in the LoRaWAN server. After commissioning, the LoRaWAN server forwards messages to and from the locks and the backend web application over secure MQTT (Message Queuing Telemetry Transport).

In operation, the end user interacts with the web application to lock/unlock a selected lock from a list of available devices, after which the web app sends a MQTT message to the LoRaWAN server, which in turn converts that into a LoRaWAN packet to the selected device.

LOTO application for demonstrating the iLock

The prototype-2 lock and iLOTO system being developed by NIOSH researchers will be used to demonstrate and evaluate the application of iLOTO for a specific LOTO scenario, in collaboration with our partner mine site. Requirements for this study were driven by an existing LOTO protocol at Central Pre-Mix Concrete a CRH Company. At the demo site, daily maintenance of the mixer drum requires a worker to crawl inside the drum (Figure 5) and remove accumulations of hardened concrete using a pneumatic rotary hammer.



Figure 5. Worker entering mixing drum to complete daily maintenance.

The first step of the LOTO protocol is to isolate electrical power from the drum, charge belt, mixer feed conveyor and hydraulic pump motors using four disconnect switches. The four disconnects are locked in the OFF position (lockout) using a long bar held in place by a single padlock (Figure 6) Verification of electrical isolation is performed by attempting to start each motor (try out), at which point the LOTO is complete and the worker may enter the drum.



Figure 6. Locking out of the power sources before daily drum maintenance.

Since the drum is a confined space in addition to the LOTO process, a confined space entry form must be filled out before entry. Both the worker who is performing the chipping and an attendant who will remain outside the drum must sign the form. Upon completion of the job, the remainder of the paper form is completed and filed away.

To verify the LOTO has been performed in accordance with the prescribed protocol, there are 9 items monitored by the system that occur in the following order:

- 1) A LOTO form is initialized.
- 2) The 4 safety disconnects are switched to the off position.
- 3) The lock is placed.
- 4) Test out is performed.
- 5) The gate is opened and closed, and mixer chipping occurs.
- 6) The gate is opened and closed after completion.
- 7) The lock is removed.
- 8) The disconnects are powered on.
- 9) The LOTO form is marked complete.

The current web-enabled monitoring system in place at the Central Pre-Mix Concrete a CRH Company, site monitors each of these steps and confirms they are done in the proper order; any deviation from the sequence of events can be recognized by the application and issues an alarm. Additionally, the system initiates a stopwatch when the LOTO form is initialized; in the event that the job takes inordinately long, an alarm is sounded.

Developing a User Interface (UI) for demonstrating iLOTO

The next step toward improving this system is to implement the prototype 2 lock and integrate its control and function into an improved UI to achieve a robust iLOTO system. When combined with the lock, this approach will be a demonstration of how a web-enabled iLOTO system can be adapted to encourage rigid compliance to LOTO protocols and to raise alarms if a protocol is not followed. Once the lock and improved user interface (UI) are complete, they will be integrated into the existing wireless monitoring system at our partner mine site and tested for functionality, ease of use, and modified based on user feedback.

The key to successful implementation of iLOTO will depend greatly on the design of the user interface. The UI must not only provide a way for users to interact with the lock but must offer a straight-forward and user friendly way for planning and executing LOTO protocols that is easy to accomplish compared to traditional methods, and at the same time, offer additional benefits that will encourage users to be more proactive about executing LOTO protocols.

While the NIOSH prototype monitoring system has proved to be useful in monitoring/confirming the proper execution of LOTO protocols, researchers intend to redesign the UI to improve its usability and to incorporate user friendly functionality specific to iLOTO. The

new design will be based on human-centered design principles and will consider various human factors in order to improve its usefulness and effectiveness. An example of this is to incorporate the principle of mental models, which is why the design of the iLock intentionally resembles a traditional padlock. The physical iLock design, along with the design of a UI that mimics the traditional LOTO process closely, ensures that the iLOTO system matches the mental models of the users [7]. Given that the users of the iLock are experienced with LOTO, it is critically important that the iLOTO system does not conflict with the users' idea of how the procedure is typically performed.

Another key factor that will be considered is that the UI must help improve the "situational awareness" (SA) of workers. SA is considered "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [8]. These three concepts (perception, comprehension, and projection) are sometimes referred to as the "stages" of SA. In general, SA represents the mental model of the state of your environment and can be described as knowing what is happening around you [9].

Ideas for improving SA during iLOTO were gleaned from a recent study in which researchers identified causal factors for various difficulties in performing LOTO procedures and encouraged designs that aid the worker in developing an accurate understanding of the environment around them [9]. Prominent results of that study included identifying the following factors and providing the associated recommendations:

- 1) *Providing Consistency and Standardization* – Poor standardization of information relates to problems in comprehending various pieces of information, including for example, tag colors and their uses or visual aids in work instructions. This pointed to the need for developing clear protocols for each machine requiring LOTO and the ability to easily access this information when a worker needs it. In the context of a web-enabled UI, this could mean a "work procedure" tab that lays out a LOTO protocol in terms the user is familiar with.
- 2) *Improving Adequacy of Procedures and Validity of Information* – The study results claim, "Inadequate procedures and outdated information hinder comprehension." This factor points to the need for a way to easily update work instructions and update the worker when changes have been made.
- 3) *Making Information More Explicit* – It is important to use familiar terminology and to highlight important points to the user. In the context of a web-enabled UI, this could mean that when the device is locked out, the user will see a page with red colors and bold text "LOCKED OUT."
- 4) *Improving Communication Structure* – The authors found that poor communication between workers greatly inhibits the effectiveness of the third stage of SA (projection) when locking out equipment. Improvement for this factor includes providing each worker with the ability to know the location of other workers, such as providing the time and specific machine another worker locked out. In the context of a web-enabled UI, this could mean a "work log" tab.

After redesigning the UI, the iLock will be used in concert with the new UI to demonstrate the implementation of iLOTO at the partner mine site. The final stage of the project will be to evaluate any resulting improvement in worker SA. To that end, it would be beneficial for the user interface to be refined through a multi-stage, iterative process. Feedback will be solicited from stakeholders, test sites, and experts in human factors and then applied to a series of software revisions. Additionally, the data will be filtered to the end user to avoid extraneous details or distractions, with the goal being to display critical information by default and allow customization as desired.

CONCLUSION

Two prototype smart locks have been designed and built with an eye toward demonstration and evaluation of iLOTO. The final prototype will be tested in concert with a NIOSH-developed existing wireless

monitoring network at a partner mine site. The iLOTO system will be integrated with the existing user interface and allow electronic tracking and confirmation of the lockout/tagout process. The monitoring of safety disconnects and access points coupled with the iLock have the potential to increase SA and ensure that LOTO protocols are rigidly followed. Additionally, the system will be capable of archiving LOTO data, complete with timestamps and user authentications. The long-term vision is that the iLock will be integrated into a larger wireless/wired monitoring system that could be scaled to larger installations with hundreds of sensors in operation. This is expected to save time, improve workers' SA, and reduce accidents in the workplace.

Future research will include developing and demonstrating a hybrid sensor network (including both wireless and wired sensors). Wired sensors have the advantages of not requiring battery replacement and can also be included in mine typical Supervisory Control and Data Acquisition (SCADA) systems. A major advantage of wireless Internet of Things (IOT) types sensors is the ease of physical installation, however they may not be as easily integrated into a traditional SCADA system due to dissimilar data communication protocols. While wireless networks are improving steadily, the mesh network currently employed at the partner mine [5] has proven unreliable. Based on these findings, it seems that at present the use of wireless IoT-type nodes should be confined to applications where their failure can occur safely and will be easily detected. Alternatively, an IoT system of this sort could prove effective if it is maintained by a highly trained individual who monitors the network closely in perpetuity.

Future versions of the iLock design may also include the ability for the lock to identify which piece of machinery or electrical box the lock is powered, using radio frequency identification and nearfield chip technology. Additionally, to help ease the transition from the familiar mechanical lock and to provide a backup should wireless connectivity fail, a hybrid version that includes a physical key will be investigated. This physical backup would only allow the lock to be unlocked with a key when all the virtual locks have been removed.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement of NIOSH. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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